VARIATIONS IN RAINFALL IN CALIFORNIA.[1]

By WILLIAM GARDNER REED.

That the seasonal precipitation for stations in California varies widely from year to year is well known and there is, at least in some instances, a correspondence of dry and wet seasons in different parts of the State. In view of the economic importance of rainfall to the State of California and also of the fact that correlations of wet and dry seasons have been made covering a period before the beginning of the records in the State, it was deemed advisable to undertake a careful investigation of the records published as trustworthy by the United States Weather Bureau to determine the relations of wet and dry periods and to ascertain if a periodicity of wet and dry seasons exists; the area of the State suggested that there might be more than one rainfall unit, and the study was directed also to the determination of the extent of these units and to the relations between such as might be found. This paper presents the results of a preliminary study of the conditions during the period from 1880 to 1910. The data are from the published records of the United States Weather Bureau for about 30 stations. No attempt has yet been made to supply gaps in the data, as it was thought best to begin with data about which there could be no question that they represent actual rainfall conditions at particular places. Later it may be possible to make use of partial or interpolated data, but at first this was not regarded as admissible.

Because of the winter maximum of rainfall and the dry or nearly dry midsummer, the time unit in a rainfall discussion for California must be a rainfall year, beginning at some time during the dry season; as it is customary to make use of a rainfall year for California which begins July 1, this year is locally known as a "rainfall season." Fortunately California is so situated that the whole State is included in the region of the "subtropical" rainfall régime and, therefore, it is necessary to consider only variations in the seasonal amounts of rainfall in the different parts of the State as long as the study is restricted to California. If a comparison between the rainfall variations in California and those in the rest of the United States or other parts of the world is to be undertaken, there must be some compromise to obtain a satisfactory time unit of rainfall amounts, unless the seasonal amount of precipitation in California is to be compared with the amount for some other unit in another region. For portions of the country in which the rainfall distribution is uniform or nearly so throughout the year the calendar year, beginning January 1, and a seasonal year, beginning July 1, are equally satisfactory as time units; the calendar year is generally made use of for simplicity of statement and from custom. For the portions of the country which have a summer maximum, or a distinct summer rainfall, the calendar year, or at least a year beginning at some time during the winter, is desirable; and, as the calendar year conforms with custom, this year is made use of. Therefore, in all parts of the country, except in the Pacific Coast region, the calendar year is the accepted time unit for rainfall; but in this region the calendar year brings together in the same time unit a spring and an autumn which belong to different rainfall units, and separates the spring and the autumn which belong together. For the present, at least, no attempt will be made to correlate Californian conditions with those of other regions, although it may well be that the amount of precipitation in a California season bears some very close relation with the amount in the following or preceding calendar year in other parts of the country, or with other units elsewhere. A reasonable degree of order in the California correlation seems desirable before attempting to group the conditions over a wider area.

For a study of this kind it is essential that no data, other than the actual measurements of precipitation, checked and certified by a recognized authority, be used. Unless this is the case the records can not be regarded as sufficiently comparable to be subjected to rigid statistical treatment. However valuable botanic and geologic data may be, and there can be no question that such records are of immense use when properly read, a determination of rainfall conditions should in the first place be determined by the use of rainfall statistics. After this has been done, the botanic or geologic record may be examined for parallelisms, and these records may be translated into terms of rainfall; but in every case such use of natural records involves a translation from one type of record into an entirely different type. There can, of course, be no doubt that the natural records are true and correct, but there are almost unlimited possibilities for incorrect interpretations of these records.

This study is based on the published records of the Weather Bureau, including all the stations which have carried on continuous observations of rainfall since 1881. There are twenty-eight such stations, if Yuma, Arizona, where the observations were made at Fort Yuma, California, from 1870 to 1875 and which station may be regarded as representing southeastern California conditions, is included in the list of California stations. Eureka was also included in the hope of determining the conditions in the regions where summer rains are not as rare as in central California. The map, figure 1, shows the approximate location of the stations used. The following table shows the length of record at each station, the numbers are those used to mark the locations on the map:

Number (See fig. 1).	Station.	Year of beginning of record.	Number (See fig. 1).	Station.	Year of beginning of record.
1	Eureka	1886	16	Santa Barbara	1867
2	Ukiah	1877	17	Los Angeles	1877
3	Calistoga	1873	18	San Diego	1850
4	Napa	1877	19	Red Bluff	1878
5	Fort Ross	1875	20	Tehama	1871
6	Oakland	1874	21	Chico	1871
7	San Francisco	1849	22	Auburn	1871
8	San Mateo	1874	23	Sacramento	1849
9	Niles	1871	24	Stockton	1867
10	San Jose	1874	25	Modesto	1871
11	Santa Cruz	1873	26	Fresno	1881
12	Gilroy	1874	27	Tulare	1876
13	Hollister	1874	28	San Bernardino	1870
14	Soledad	1874	29	Yuma (and Fort Yuma).	1870
15	San Luis Obispo	1869			

There are a number of other stations for which data for one or more months have been interpolated, but as

[1] Presented at the meeting of the Cordilleran Section of the Geological Society, April 11, 1913.

interpolation is based upon the assumption that rainfall conditions are not entirely local, and one of the objects of this study is to determine how far conditions in different parts of the State are identical, no interpolated data have been used, and the record from no station not complete since 1881 has been considered. In a more intensive study it will be possible to use those parts of the records which are the results of actual observation, but, as will be seen later, the method of smoothing the curves for use introduces whatever error there may be in interpolation over a period of five years.

Although the method of comparing rainfall data by means of the plotted curves has its dangers, these are far outweighed by the advantages of the method. The relative significance of numbers is difficult to comprehend when there are a great many of the numbers; maximum

FIG. 1.—Map of California, showing the location of the stations. (For the names of the stations and the length of the records *see* page 1785.)

and minimum amounts appear only upon close examination; and the relative position of the maxima and minima does not stand out as clearly as in curves. In the consideration of a number of stations as great as even that of the California stations with 30-year records, curves become almost a necessity for a comparative study.

The first attempt was, of course, to deal with the curves plotted from the actual data computed from the observations by adding together the amounts of precipitation for each season at each station. This is the form in which the data are published by the Weather Bureau. The curves for a number of long-term records were plotted, but an examination of the curves showed that the fluctuations from season to season are so wide and so irregular that any general tendencies lasting more than one season are very poorly shown or entirely obscured, except in the more extreme cases; and even in the extreme cases the amplitude of the variation and the position of the middles of the excess and deficiency periods were more or less obscure. A fair sample of the type of curve obtained is shown by figure 2, which is the seasonal amount of rainfall at San Francisco from 1849 to 1912, inclusive.

This state of affairs necessitated some simplification of the curves before a successful comparison could be made. Such a simplification involves a suppression of the actual amounts of rainfall for the individual years or seasons and the substitution of artificial amounts which shall show the general conditions without too much emphasis upon the special conditions which control the actual amount in a single season. To obtain such conditions it is usual to "smooth" the curves. Various methods of smoothing rainfall curves have been discussed elsewhere.[1] Free-hand smoothing is not desirable because of the extreme complexity of the curves and the tendency to personal bias, especially toward introducing more parallelism between the curves for different stations than exists. Smoothing by the use of a formula, although involving an immense amount of computation, offers the most sat-

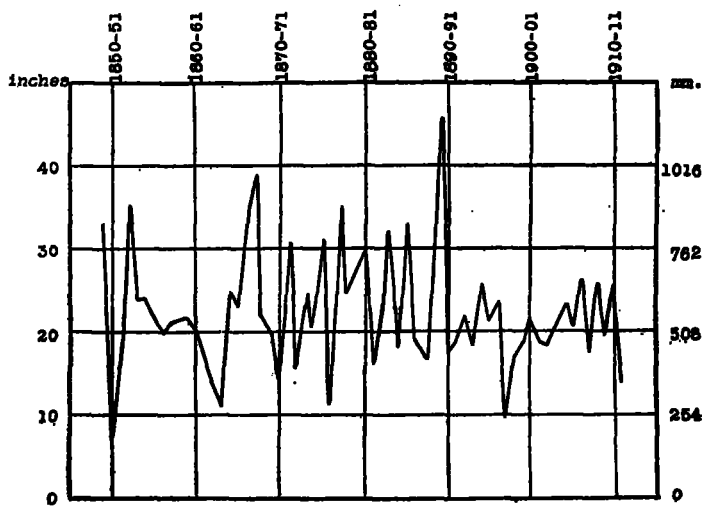

FIG. 2—Seasonal rainfall at San Francisco, Cal., 1849-1912.

isfactory curves. Differences in formulæ will give different curves; but, if the same formula is used for all the curves, the results will be comparable, and if the formula has been found satisfactory in showing general conditions, it will serve the purpose of furnishing smoothed curves for comparison, even though the individual curves are not quite correct. As Blandford's formula has been satisfactory in showing the general tendencies, it has been adopted for this study. In this formula [2] the position of the curve for any season depends upon the amounts for the two seasons next preceding and the two next following, as well as upon the amount for the season in question; the more distant seasons are weighted less heavily than the one for which the "artificial" amount is desired. From the curves thus plotted the tendencies restricted to single years show only in a restricted manner, while those extending over a series of years retain their force.

After plotting the curves for the stations with the proper records, these curves were attached to a large map of California at approximately the correct geographical location of the stations, so that the geographical relations of the curves might be studied and to determine if there

[1] See Beals, E. A. Variations in Rainfall, Mo. Weather Rev., vol. 39, pp. 1448-1452. 1911. Reed, W. G. The Rainfall of Berkeley, Cal., Univ. Cal. Pub. Geog., vol. 1, No. 2, pp. 63-79. 1913.

[2] $\frac{A\ 4B\ 6C\ 4D\ E}{16}$ = C', where A, B, C, D, and E are the amounts for successive seasons and C' is the corrected amount for them iddle year of the group of five seasons which is used in place of the actual amount for the season in plotting the smoothed curve.

was any similarity between the curves of the same region and if there were any differences in the different regions of the State. At the same time an attempt was made to group the curves themselves without regard to their location. By these means it was possible to provide a check to personal bias and to prevent unlike curves being forced together because of their propinquity on the map, and also to correct any tendency to overlook likenesses in

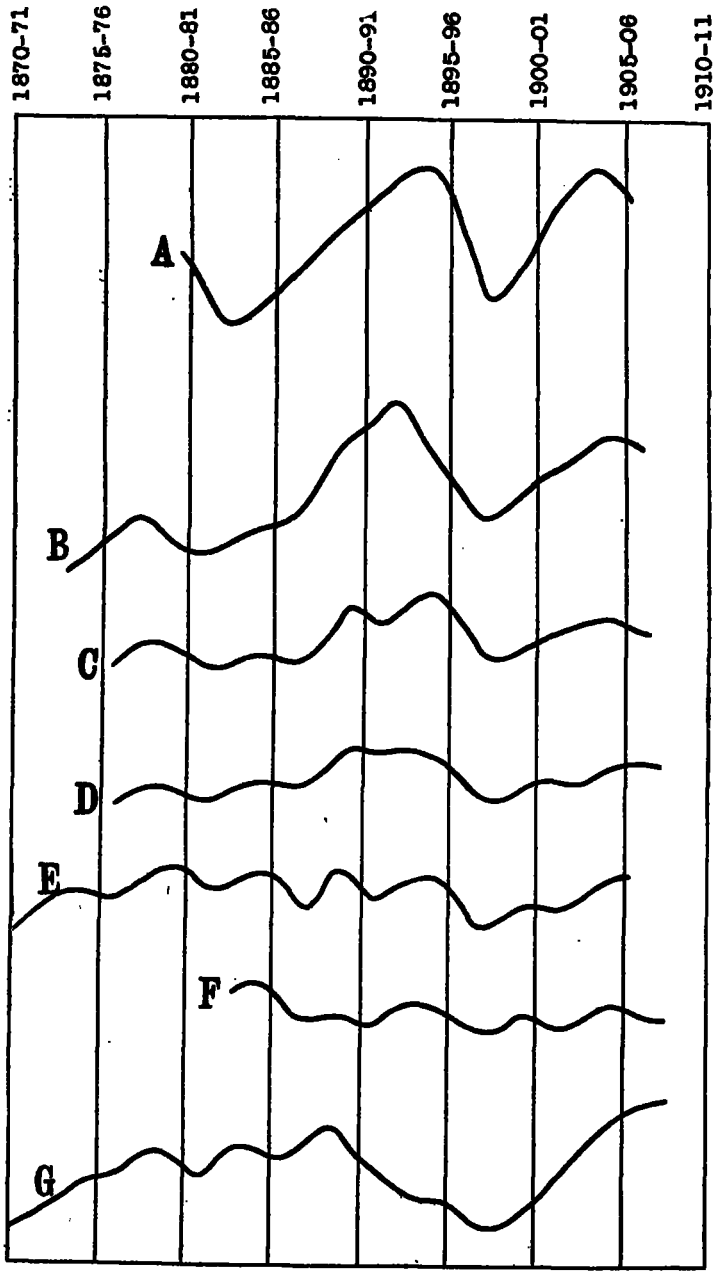

FIG. 3.—Type curves of seasonal rainfall in California:
(A) North Coast, Ukiah; (B) North Valley, Tehama; (C) Central Coast, San Mateo; (D) Central Coast, San Jose; (E) Central Valley, Sacramento; (F) Southern Valley, Fresno; (G) Southern station, Santa Barbara.

curves of stations far from each other. The groups made by the two methods correspond very closely. On the basis of the preliminary study of the curves the following types of rainfall variation have appeared: (1) a northern California type (curves A and B in figure 3), (2) a central California type, which may, perhaps, be subdivided into a coast subtype (curves C and D in figure 3) and an interior subtype (curves E and F), and (3) a southern California type (curve G).

In the region where the northern California type of rainfall variation prevails the general conditions are shown by the smoothed curves for a station in the Coast Range region, Ukiah in Mendocino County (curve A) and for a station in the Great Valley, Tehama in Tehama County (curve B). The variations in the smoothed curves show minimum rainfall conditions in the early eighties, maximum in the early nineties in the Great Valley and in the middle nineties in the Coast Range region, minimum again in 1897–98 and a maximum in 1904–05 in both the Coast Range and the Great Valley regions. This last maximum is followed by a tendency toward a minimum but the curve has not been carried far enough along to show

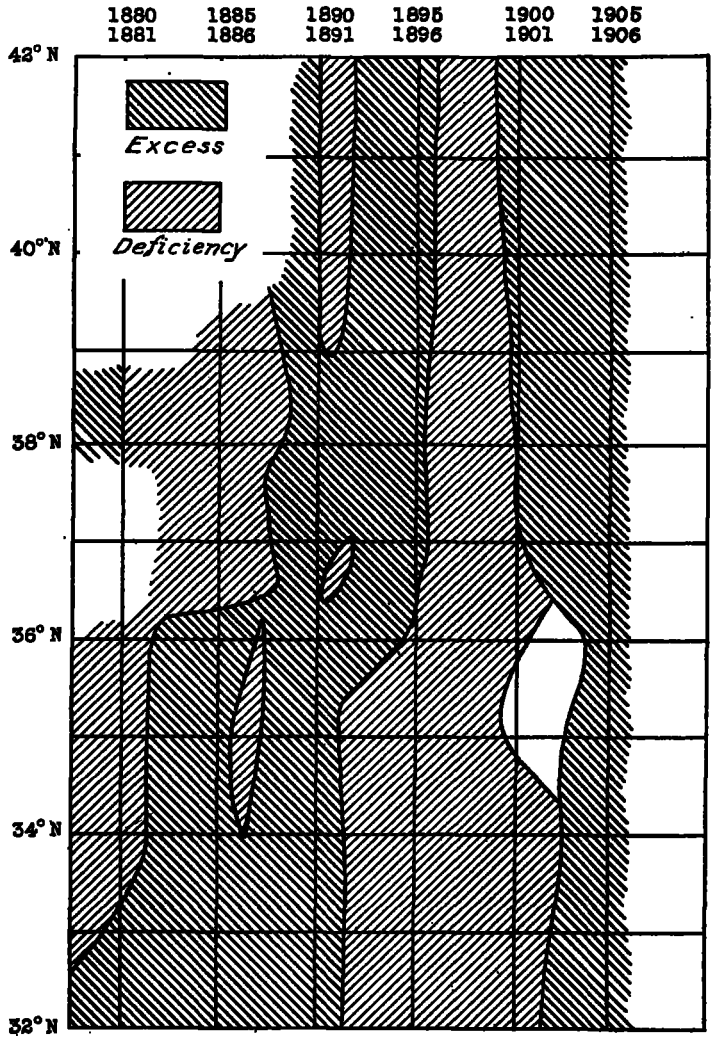

FIG. 4.—Rainfall conditions at coast stations from smoothed curves.

the date of the minimum conditions. The amplitude of the oscillation in this region is somewhat regular, but the period, if any exists, has not yet appeared from the curves as there has been but one complete oscillation during the term of the record and the time of this complete oscillation was not the same at all the stations studied.

In figures 4 and 5 the departures from the average rainfall for the time of the record at each station have been shown at the latitude of each station by years, the ordinates representing the latitude of the station and the abscissæ the years of the record. In figure 4 the data for stations in the Coast Range region and the southern California coast have been plotted and in figure 5 those for the Great Valley, including the Tulare Basin, and the

southern California region away from the coast. These diagrams show similar conditions of departure over the northern Coast Range and Great Valley regions. The diagrams show nothing of the character of the curves of rainfall variation, except the fact of excess or deficiency from the average, and, as the averages at the different stations are based on different years of record, they can not be regarded as absolutely trustworthy in showing the actual conditions, although they are probably valuable as indicating tendencies.

A feature of figure 4, the Coast group, is the beginning of the first epoch of excess precipitation five years or more earlier in the southern portion than in the northern;

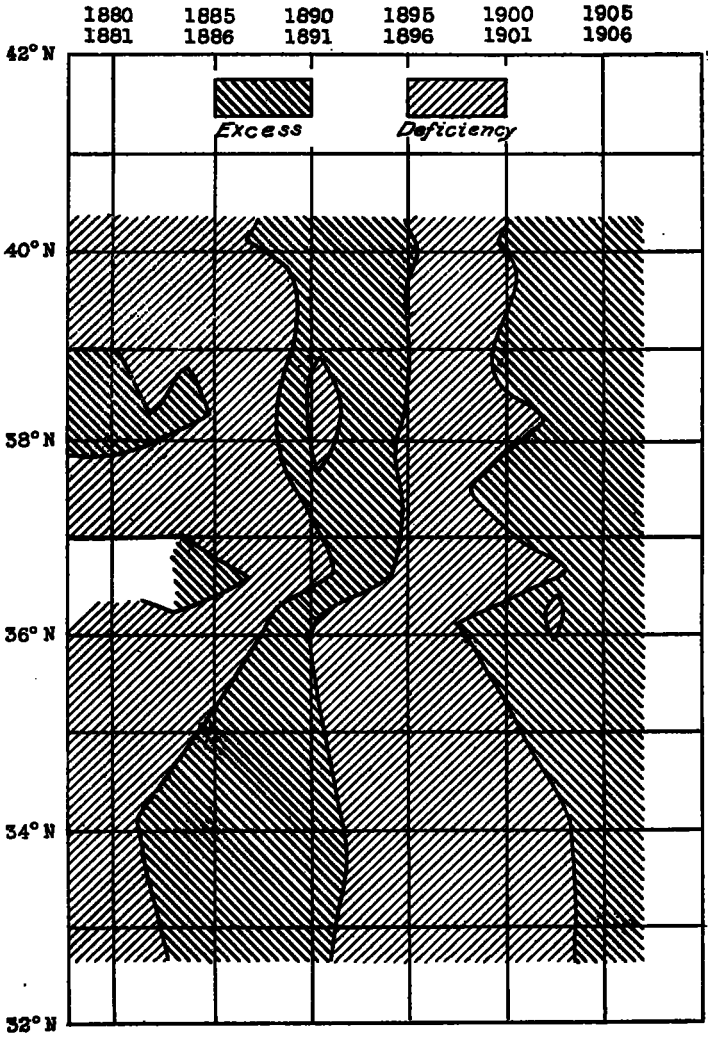

FIG. 5.—Rainfall conditions at interior stations from smoothed curves.

the advanced beginning in the south of the epoch of deficiency of the late nineties is nearly as marked. The boundaries of the belts are less regular in figure 5, the Interior group, but the same tendencies are shown here. The division between the southern and the northern portions of the regions is at about latitude 36½°. The epoch of excess which ends the record in each case does not show the early beginning in the south.

The district in which the northern California type of variation predominates includes the Coast Range region north of San Francisco Bay, with the exception of the southern part of Napa County and the northern end of the Great Valley of California. The records in the extreme northern part of the State are few in number and are all of shorter length than the minimum adopted for this study. It may later be advisable to attempt to determine the conditions north of the region for which the records are of reasonable duration by a study of the shorter records or the consideration of the Oregon records. For the present it is sufficient to state that data are wanting in the Coast Range region north of Ukiah (except Eureka, which has a record shorter than the adopted minimum), and in the interior there are no available records of the required length north of the northern end of the Great Valley. The eastward extent of the area has not been determined, as the records from the stations in the Sierra Nevada Mountains are of short duration; except for the stations along the line of the Central Pacific Railroad and east of Auburn the records all have breaks, which render them unavailable at the present. The stations in the Coast Range region, where the northern California type of curve of rainfall variation is to be found are Eureka, Ukiah, Calistoga, and Fort Ross; in the Great Valley the stations are Tehama, Red Bluff, Chico, and Auburn.

The central California type of rainfall variation is found in the Coast Range region from the Napa Valley southward to San Luis Obispo County, about latitude

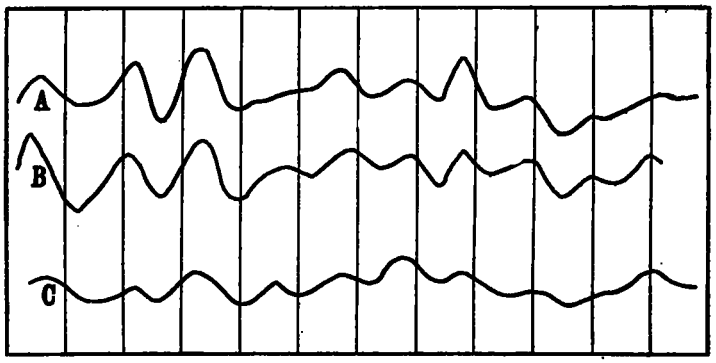

FIG. 6.—Smoothed curves for longest-period stations: (A) San Francisco; (B) Sacramento; (C) San Diego.

36°. The exact boundary can not be determined because of lack of stations, but it is probable that there is a gradual transition rather than a sharp dividing line. The stations available in the Coast Range region include Napa, Oakland, San Francisco, San Mateo, Niles, San Jose, Santa Cruz, Gilroy, Hollister, and Soledad. The type curves for this region are San Mateo (curve C) and San Jose (curve D). The curve for San Francisco (see figure 6) resembles those for the stations in the Great Valley more than those for the other Coast Range stations.

The interior subtype of the central California region includes all the Great Valley from its extreme southern end (the Tehachipi Mountains) to a point somewhere north of Sacramento. This region includes the Tulare Basin at the southern end of the Great Valley, although this basin is a region of interior drainage, except in very unusual cases. The available data are from Sacramento, Stockton, Modesto, Fresno, and Tulare. Typical smoothed curves for the central California region are those for Sacramento (curve E, fig. 3) and Fresno, representing the Tulare Basin conditions (curve F, fig. 3). Their difference from the Coast Range curves is apparent. There is a difference in the character of the curves from the Coast Range stations and those from the Great Valley stations which has led to the suggestion of

two subtypes in the region, but these differences are, in general, the appearance of the curves rather than in specific, tangible features and may be due to total amounts of rainfall as much as anything. In the central California group of stations there is a tendency toward a greater number of maxima and minima than in the region to the north and that to the south. This is not so clearly shown in the diagrams of departure from the average conditions, as the tendency is to break the maximum with a weak minimum, and the minimum with a weak maximum, and not to show a variation which takes the curve below or above the average. Further smoothing of the Coast Range curves would bring them into more or less accord with the curves for the northern stations, but such is not so clearly the case with the Valley stations and with San Francisco.

The variations in rainfall in the Tulare Basin (see curve for Fresno, F in fig. 3) show the same type of oscillation as the other curves for the Great Valley stations in the central California region, but the amplitudes of the oscillation are not always the same. In figure 5 the times of the periods of excess and deficient precipitation do not agree with the times for the other part of the Great Valley, but this is probably due to the shorter observation period of the record and the consequent different relation between the average amounts and the seasonal amounts shown by the curves.

The whole of the State south of the central region, that is south of Monterey County and the Tehachipi Mountains, shows the same type of rainfall variation. The curves from the coast region and from the desert are very similar, in spite of the wide differences in the amounts of rain in the different parts of the region. The curve for Santa Barbara (G in fig. 3) is typical of the region. The available stations in the region are San Luis Obispo, Santa Barbara, Los Angeles, San Diego, San Bernardino, and Yuma. It is to be regretted that there is no station in the Mojave Desert or in Owens Valley which is available for this study. There are partial records for stations in both these regions, but there is none which meets the minimum requirements of the preliminary study. When a proper statistical method has been found it will probably be possible to use such parts of the records as may be available and to get some idea, at least, whether these regions belong to one of the three rainfall districts or whether they constitute a fourth district. For the present they must be classed with the extreme northern part of the State and the Sierra Nevada Mountains and omitted for want of data.

Perhaps the most striking condition shown by the preliminary study is the difference in the rainfall variation in different latitudes in California. When the curves were placed in their proper geographical position on the map of the State, it was seen that there was a general series along the coastal part of the State, in the region which may be called, for convenience, the Coast Ranges, and another series from the northern end of the Great Valley southward across the desert region of the southeastern part of the State. The departures from the average seasonal rainfall for stations in the Coast Range region are shown at the proper latitudes for the stations in figure 4, and similar relations for the interior stations are shown in figure 5. The attempt to classify the curves on the basis of the latitude of the stations alone was not successful, and the same was true in the attempt to classify the excesses and deficiencies on a simple latitude basis. After the curves had been divided into a Coast Range class and an interior class, the diagram of excesses and deficiencies for each class with the stations arranged by latitude became much simpler.

In drawing the diagrams the divisions between the seasons of excess and those of deficient precipitation were marked along the line representing the latitude of each station. After these divisions had been indicated, the points were connected freehand and the areas of excess and deficiency indicated by shading. The two diagrams (figs. 4 and 5) show only the algebraic signs of the departtures from the averages and indicate nothing in regard to the amount of the departure. As the departures are measured from the averages of the periods of the records and these do not all represent the same seasons the diagrams are essentially unfair and must be inaccurate in many places. But in spite of this, at least since 1881, the oscillation in the south is shown to be of a longer period than that in the central region which is also indicated by the curves, where no averages are shown and where the oscillation without regard to average conditions is all that appears.

The season of 1889–90 is remembered as one of great excess of rainfall. In most cases the smoothed curves show that this season occurred during an epoch of rainfall in excess of the average. This is true for all the stations in the Coast group and for those in the Valley group, with the possible exception of stations in the Tulare Basin, where the "artificial" amount was not far from the average amount for the period of the records. The season of 1897–98 was one of the driest within the 30 years covered by this study in most or all of the stations in California; this is the only reputed "dry year" in the period under discussion, as the seasons ending June 30, 1912, and June 30, 1913, are at the end of the record and can not appear in the smoothed curve. The season appears in figures 4 and 5 as a part of an epoch of precipitation lower than average in amount.

It should be noted, however, that the season of 1889–90 is not at the crest of the epoch of excess for the smoothed curves throughout the State and that the trough of the period of deficiency is not in all cases at the season of 1897–98. But it is true that these strongly marked seasons had the same characteristics throughout the State and in so far as the characteristics of single seasons of wide departure may be trusted they show State-wide conditions. Where the departures are not so great in amount, the conditions of excess or deficiency from the average are not nearly as well marked and the extent of the area in which like conditions occurred is much smaller.

While many interesting lines of investigation are suggested by the diagrams, it seems best to present them at this time without further comment, as the proper statistical method for the treatment of the data has not yet been determined. That the variations in different regions have been similar, although not identical, is shown by figure 6, where the smoothed curves for the longest records in California, A for San Francisco, B for Sacramento, and C for San Diego, have been plotted with the same time scale and equal amount scales. The most noteworthy features of this set of curves are the occurrence of the crests and troughs at the same seasons in the great majority of the cases, the somewhat close parallelism between the San Francisco and Sacramento curves, and the considerable difference in the amounts of the departures shown by the San Diego curve from the amounts shown by the other two curves.

In view of the incomplete state of the work and the absence of any satisfactory statistical method of handling the data, the study has not been carried further. The

preliminary investigation indicates the necessity of a careful study of all the records, in order to determine exactly what the rainfall variations in the State have been, so that these results may be compared with the evidence of an indirect character to determine just what rainfall conditions are associated with botanical and geological features, and thus the curves of accurate rainfall measurements carried back of the beginning of the data.

On the basis of a study of the rainfall data for stations in California with a record of 30 years' duration the following tentative conclusions may be drawn:

1. Rainfall in California varies in amount within wide limits.

2. In a very general way the variation is similar in character but not in amount throughout the State.

3. Variations more or less similar in character and amount are to be found in each of the following districts of the State: (*a*) California north of latitude 38° or 39°; (*b*) the Coast ranges from Napa County south to San Luis Obispo County; (*c*) the Great Valley of California south of latitude 39°; (*d*) Southern California, that part of the State south of San Luis Obispo and the Tehachipi Mountains. No data are available for Owens Valley and the Mojave Desert, or for northern and eastern California.

4. The period of oscillation of the seasonal amounts of rainfall is longer south of latitude 35° than north of this line.

5. The "wet year," 1889–90, and the "dry year," 1897–98, were nearly or quite State-wide. Data are lacking for the other reputed wet and dry years.

6. It is evident that careful statistical analysis of the data and rigid treatment of the results are necessary before any safe conclusions can be drawn regarding rainfall oscillations in the State.

UNIVERSITY OF CALIFORNIA,
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